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Modeling the stress versus settlement behavior of shallow foundations in unsaturated cohesive soils extending the modified total stress approach

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Abstract

The mechanical behavior of unsaturated soils can be interpreted using either modified total stress or a modified effective stress approach depending on the type of soils and various scenarios of drainage conditions of pore-water and pore-air. Recent studies suggest that the bearing capacity of unsaturated cohesive soils can be more reliably estimated using the modified total stress approach (MTSA) rather than the modified effective stress approach (MESA). In the present study, a modeling technique (extending Finite Element Analysis, FEA) is proposed to estimate the bearing capacity of shallow foundations in unsaturated cohesive soils by simulating the vertical stress versus surface settlement behaviors of shallow foundations extending the MTSA. The proposed technique is verified with the model footing test results in unsaturated cohesive soils. Commercial finite element software, SIGMA/W (GeoStudio 2012, Geo-Slope Int. Ltd.) is used for this study. Details of estimating the unsaturated soil parameters (i.e. total cohesion, modulus of elasticity and Poisson's ratio) required for the FEA are also presented taking account of the influence of matric suction. Good agreements were observed between the measured bearing capacity values and those from the FEA extending the MTSA.

Keywords: Unsaturated soil; Finite element analysis; Stress versus settlement; Shallow foundation; Modulus of elasticity; Poisson's ratio (**IGC**: E3/E13/E14)

1. Introduction

The bearing capacity of saturated soils can be estimated by extending either the effective stress approach (ESA; Terzaghi, 1943) or the total stress approach (TSA; Skempton, 1948). Criterion for determining appropriate approach between the ESA and the TSA are based on the soil type and drainage condition of pore-water during the loading stages. Shallow spread footings are commonly used as foundations of light structures. In many cases (especially in arid and semi-arid regions), the water table is relatively deep, and the pressure bulb typically lies within the vadose zone where soils are in unsaturated condition with negative pore-water pressure. Soil desaturation associated with lowering the natural ground water level or water evaporation from the soil surface results in an increase in the bearing capacity compared to the saturated soil condition. Various research related to the bearing capacity of unsaturated soils suggest that this increase can be attributed to the influence of soil suction (Broms, 1964; Steensen-Bach et al., 1987; Fredlund and Rahardjo, 1993; Oloo et al., 1997; Costa et al., 2003; Rojas et al., 2007; Balzano et al., 2012). Nevertheless, there are still uncertainties

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as to which approach (i.e. ESA or TSA) is more appropriate in the reliable estimation of the bearing capacity of unsaturated soils. Vanapalli and Mohamed (2007) and Schanz et al. (2011) showed that the bearing capacity of unsaturated sandy soils can be reliably estimated extending the ESA taking account of the influence of matric suction. Oh and Vanapalli (2013a) conducted model footing tests in unsaturated glacial till (i.e. Indian Head till) and concluded that the TSA based on the unconfined compressive strength of unsaturated soils can provide a more reasonable bearing capacity of unsaturated cohesive soils. These research studies related to the bearing capacity of unsaturated cohesionless and cohesive soils indicate that the bearing capacity of unsaturated soils should be estimated considering the type of soil and the drainage conditions of pore-water and pore-air. The ESA and the TSA for unsaturated soils are designated as the modified effective stress approach (MESA) and the modified total stress approach (MTSA), respectively.

In-situ plate load test (PLT) is one of the most reliable testing techniques for estimating the bearing capacity of shallow foundations. In-situ PLTs are typically carried out on soils that are in a state of unsaturated condition; hence, there are uncertainties in analyzing the in-situ PLT results in terms of scale effect and matric suction distribution profile with respect to depth (Oh and Vanapalli, 2013b). For this reason, numerical analysis is commonly used as an alternative to the in-situ PLTs to estimate the bearing capacity of unsaturated soils. The results from numerical analyses provide technically acceptable solutions for soil-structure stress and deformation characteristics below shallow foundations (Hanna, 1987; Consoli et al., 1998; Bose and Das, 1997; Lee and Salgado, 2002; Edwards et al., 2005; Hjiaj et al., 2005; Osman and Bolton, 2005). Limited studies were undertaken to predict the variation of bearing capacity of unsaturated soils with respect to matric suction by simulating the stress versus settlement (hereafter referred to as SVS) behaviors of shallow foundations in unsaturated soils using the Finite Element Analysis (FEA) (Abed and Vermeer, 2004; Oh and Vanapalli, 2011a; Le et al., 2013). Various constitutive models are available in the literature to simulate the deformation characteristics of unsaturated soils (Alonso et al., 1990; Kohgo et al., 1993; Wheeler and Sivakumar, 1995; Cui and Delage, 1996; Karube, 1997; Sun et al., 2000; Gallipoli et al., 2003). These models are comprehensive and can model many scenarios of different geotechnical problems extending the principles of unsaturated soil mechanics. The mathematical framework proposed by Borja (2004) to estimate deformation and strain localization in unsaturated soils considering both drained and undrained conditions is a notable contribution in this direction. However, these constitutive models require various soil parameters and determination of these parameters from experimental investigations is rather difficult, time consuming and cumbersome (D'Onza et al., 2015).

Oh and Vanapalli (2011a) proposed a simple numerical modeling technique for engineering practice applications to simulate the SVS behaviors of shallow foundations for unsaturated cohesionless soils based on the MESA. Two main parameters are required for extending this simple technique; namely, total cohesion and elastic modulus. In the present study, this numerical modeling technique is extended to simulate the SVS behaviors of a model footing in an unsaturated cohesive soil based on the MTSA. The commercial finite element software, SIGMA/W (GeoStudio 2012, Geo-Slope Int. Ltd.) was used for the FEA. Comparisons are made between the measured SVS behaviors and bearing capacity values and those estimated using the MESA, MTSA, and FEA.

2. Background

2.1. Estimation of bearing capacity of unsaturated soils using the MESA

In unsaturated cohesionless soils, (i) both the pore-air and pore-water in soils are in drained condition during the loading stages; and, (ii) general failure mode is expected for relatively high-density soils. These two conditions justify the use of MESA in estimating the bearing capacity of unsaturated cohesionless soils using the effective shear strength parameters (c', ϕ', and ϕ^b). Oloo (1994) proposed a method that can be used to design unpaved roads considering the influence of matric suction on the bearing capacity of pavement structures [Eq. (1)].

$$q_{ult(unsat)} = [c' + (u_a - u_w)\tan\phi^b]N_c\xi_c + q_0 N_q \xi_q + 0.5B\gamma N_\gamma \xi_\gamma \quad (1)$$

where $q_{ult(unsat)}$ = ultimate bearing capacity of an unsaturated soil, c' = effective cohesion, ϕ' = effective internal friction angle, ϕ^b = internal friction angle due to the contribution of matric suction, $(u_a - u_w)$ = matric suction, γ = soil unit weight, q_0 = overburden pressure, B = width of footing, N_c, N_q, N_γ = bearing capacity factors, and ξ_c, ξ_q, ξ_γ= shape factors.

Vanapalli and Mohamed (2007) further improved Eq. (1) to estimate the ultimate bearing capacity of surface footings in unsaturated soils by taking account of nonlinear variation of shear strength with respect to suction (Vanapalli et al., 1996) [Eq. (2)].

$$q_{ult(unsat)} = \begin{bmatrix} c' + (u_a - u_w)_b(1 - S^{(\psi_{BC})}\tan\phi') \\ +(u_a - u_w)_{AVR} S^{(\psi_{BC})}\tan\phi' \end{bmatrix} N_c\xi_c + 0.5B\gamma N_\gamma \xi_\gamma \quad (2)$$

where $(u_a - u_w)_b$ = air-entry value, $(u_a - u_w)_{AVR}$ = average matric suction, S = degree of saturation, ψ_{BC} = fitting parameter for bearing capacity, N_c, N_q = bearing capacity factors from Terzaghi (1943), N_γ = bearing capacity factor from Kumbhokjar (1993), and ξ_c, ξ_q, ξ_γ = shape factors (Vésic, 1973).